

Across Space and Time

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*: Keynote Address

⊗: Nick Ryan Award

Palmyra Revisited from Space – High-Resolution Satellite Prospection of a UNESCO World Heritage Site

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Abstract:

The launch of TerraSAR-X widened the application of Synthetic Aperture Radar (SAR) in the archaeological prospection tremendously. SAR now can be used effectively for the integrated geophysical prospection of huge ancient settlements and cities such as Palmyra. On the one hand, ground-based methods like magnetometry and resistivity can provide detailed insights into the buried archaeological remains. On the other hand, it is possible to get a fast overview of a site and its cultural landscape by space-borne survey methods, e.g. optical satellite photos or satellite radar. This paper will show the results of an integrated geophysical prospection by magnetometry, resistivity, satellite photos and radar in the area of the ancient Palmyra. While the first two methods could prove the existence of a Hellenistic town south of the Wadi el Kubur and map its layout in detail, the space-borne results provide an overview over the upstanding remains, as well as several new structures of the buried archaeology of this famous caravan city in the Syrian Desert.

Keywords:

Synthetic Aperture Radar, TerraSAR-X, Remote Sensing, Magnetometry, Syria

1. Introduction

In the last decades, integrated geophysical prospection has become a very important tool in archaeology (Fassbinder 2007; Gaffney and Gater 2003; Neubauer et al. 2002; Scollar et al. 1990). Modern excavations often need prior geophysical prospection, as large-scale excavations cannot be carried out anymore today because of cost reasons and the survey results give strong hints for promising areas. Furthermore geophysical prospection is a non-destructive tool for the understanding of an archaeological site in its context. Therefore, in 1997/98 a cooperation between the Bavarian State Department of Monuments and Sites (BLfD) in Munich and the Institute of Classical Archaeology of the University Vienna was established for geophysical surveys by magnetometry and resistivity prospection in the proposed area of the Hellenistic

part of Palmyra. Since 2011, another cooperation of the BLfD and the German Aerospace Centre (DLR) in Oberpfaffenhofen has the goal to investigate the whole town by remote sensing with optical and radar satellites. The advantage of satellite-based archaeological prospection is the accessibility of even very remote archaeological sites, which often cannot be surveyed by ground-based methods because of political or other reasons. To understand the development and structure of historic settlements, it is often important to survey the entire settled area.

The ancient ruins of Palmyra provide an excellent test site for geophysical methods and remote sensing because huge parts of the city remain unexcavated and nearly the whole settlement had never been overbuilt in post-ancient times. Another important factor is that the archaeological findings are covered by only a thin layer of sand and provide good contrast to the surrounding material.

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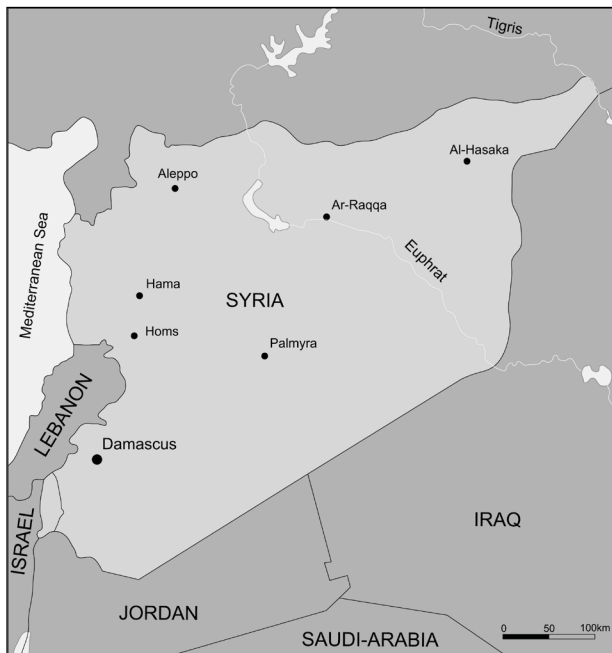


Figure 1. Map of Syria showing the location of Palmyra in central Syria, 230 km northeast of the capital Damascus.

2. Archaeological Background

Palmyra is situated 230 km northeast of Damascus in a fertile oasis in the Syrian Desert (Fig. 1). Hence, the area was settled since Palaeolithic times (75,000 BP) (Bounni and al-As'ad 1990; Browning 1979). The first written evidence can be dated to the 2nd millennium BCE, when Palmyra is mentioned in the Assyrian and Babylonian cuneiform plates of Kültepe (Cappadocia) and Mari (Syria) (al-As'ad and Schmidt-Colinet 2005b; Degeorge 2002; Michalowski 1968). Further evidence can be found for Hellenistic period occupation in the area south of the Wadi el Kubur that runs through the ancient city. When Palmyra got part of the Diadochian Empire of Seleukos in the 3rd century BCE, there was an increase in prosperity, as the Palmyrenes managed to set up the only safe caravan route in the region. In the 1st century CE Palmyra became part of the Roman province Syria (Hartmann 2001). In the following centuries, Palmyra was step by step Romanised. The most prosperous time of Palmyra came in the 2nd century CE, when the Nabatean Empire, which was the biggest enemy in caravan trade, was conquered by the Roman emperor Trajan (Degeorge 2002). This can be proved by the monumental architecture of this century, when the

well known monuments like e.g. the Bel-sanctuary, the Great Column Road and the tower tombs were erected. In this time, the Palmyrene trade network reached from Spain in the west to China in the east, but already at the end of the same century the decline began as a consequence of the Parthian wars and the associated shift of the trading route towards the north (Degeorge 2002). After the famous usurpation of Queen Zenobia in 262 CE, Palmyra was conquered by the Roman emperor Aurelian and afterwards it only served as a military post at the Roman Limes Arabicus. In 300 CE Diocletian built a new city wall and a huge fortress in the western part of the city (al-As'ad and Schmidt-Colinet 2005b; Degeorge 2002; Gawlikowski 2005; Hartmann 2001). In 634 CE it was conquered by the Arabs under their general Khalid ibn al-Walid (al-As'ad and Schmidt-Colinet 2005a; Degeorge 2002). But after the Abbasids moved their capital from Damascus to Bagdad, Palmyra totally lost its importance and it declined to a small village (al-As'ad 1987; 1993; al-As'ad, al-As'ad and Schmidt-Colinet 2005; al-As'ad and Schmidt-Colinet 2005b). In Ottoman times (16th-19th century) Palmyra was a negligible settlement, left open for the raid of the Bedouins (al-As'ad 1993).

As Palmyra today is the most important ruin site of the Hellenistic-Roman times in Syria, it was declared as a UNESCO World Heritage Site in 1980. The first systematic excavations started already at the beginning of the 20th century by Russian and German archaeological missions (Michalowski 1968). Since this time there had been excavations by archaeologists from all over the world until 2011, when the political situation made it impossible to work in Syria. However, there is still a huge amount of the ancient city that has not been documented until now. The main building material of the excavated buildings in Palmyra has been limestone, which provides a good visibility of the remains in the geophysical results.

3. Geological Background

The region of Palmyra is characterised by two different geological units. In the north and west, the mountains of the Palmyra chains which belong to the Antilebanon tower up to 1000 m ASL. For comparison: Palmyra lies at only 395 m ASL (Jux and Omara 1960; Schachinger 1987). The Palmyra

chains consist mainly of dolomites, which were used to construct the ancient buildings. They continue further towards the Euphrates River in a southwest-northeast direction. South and east of Palmyra, the Syrian Desert is situated, which is characterised by loose sand dunes. In the direct southern neighbourhood of the city, a huge sebkha, a salt plain of 330 km², can be found. This salt plain was already used in ancient times and provided one of the reasons of the wealthiness of Palmyra (Sanlaville and Traboulsi 1996).

4. Methods

4.1 Magnetometry

For the geophysical survey of archaeological sites, several ground-based methods were applied. These are mainly magnetometry, resistivity prospection and ground-penetrating-radar. Magnetometry is a successful and cost-effective tool for the detailed mapping of large areas in a reasonable time (English Heritage 2008). Total field magnetometers like the used Scintrex Smartmag SM4G Special provide the best results for archaeological prospection. The reason is that all components of the Earth's magnetic field are recorded; the resulting anomaly therefore is much stronger than the one recorded by fluxgate magnetometers, which record only one vector component. For our purpose and in order to reach the highest possible sensitivity combined with a maximum speed of prospection, the so-called "duo-sensor" configuration (Fassbinder 2010) was chosen. The sensors are therefore mounted on a wooden frame and carried in a zigzag-mode 30 cm above the ground. The profiles are oriented approximately east-west in order to minimise technical disturbances of the magnetometer probes. The Scintrex Smartmag SM4G Special magnetometer provides a measurement of the geomagnetic field with sensitivity of ± 10 pT; for comparison: the value of the geomagnetic field in Palmyra in March 1997 has been $45,440 \pm 30$ nT.

During 1997 and 1998 the solar activity and diurnal variation induced by the solar wind were very low. These linear changes in the daily variation of the geomagnetic field were reduced to the mean value of the 40 m sampling profile or alternatively to the mean value of all data of a 40 x 40 m grid

(Fassbinder and Gorka 2009). Here it is assumed that the variation of the Earth's magnetic field during one profile length of 40 m follows a linear increase or decrease in intensity. If so, it is possible to eliminate this variation for each traverse line by a reduction to the mean line value. This filters apparent linear structures parallel to the profile. Alternatively, in magnetically quiet areas it is also useful to calculate the mean value of the whole 40 x 40 m grid and use this value as described above. Additionally, by using this procedure the difference between the measurement of both magnetometer probes and the – theoretically calculated – mean value of the Earth's magnetic field was obtained. This intensity difference gave the apparent magnetic anomaly, which was caused by the magnetic properties of the archaeological structure, the soil magnetism and the geology. To cancel the natural micro-pulsations of the Earth's magnetic field, a band pass filter in the hardware of the magnetometer processor was used. The processing of the magnetometer data was achieved by some self-written resampling software and Geoscan Geoplot. Afterwards, the results were displayed by Golden Software Surfer.

Usually more than 90 % of the magnetometer data in a 40 m grid on archaeological sites vary in the range of ± 10 nT from the corrected mean value of the geomagnetic field. Stronger anomalies can be ascribed to burned structures or to pieces of iron containing slag or modern iron debris. In-situ burning, pieces of iron and the traces of hypocausts are easily distinguishable by their different direction of magnetic dipole anomalies, but also by their high intensities ($> \pm 50$ nT).

4.2 Resistivity prospection

Almost all of the Hellenistic and Roman buildings are stone constructions which have a strong contrast against the surrounding soil in electric conductivity. For this reason, the stone buildings are mapped very clearly through resistivity prospection, which is based on the apparent differences in the conductivity of the soil. Clays and marls, for example, have specific resistivity values of 3 – 100 Ohm m. On the contrary, sand, limestone and sandstone provide resistivity values of 100 – 5000 Ohm m. In conductive wet soil the resistivity of stone constructions is several degrees higher than in the surrounding soil.

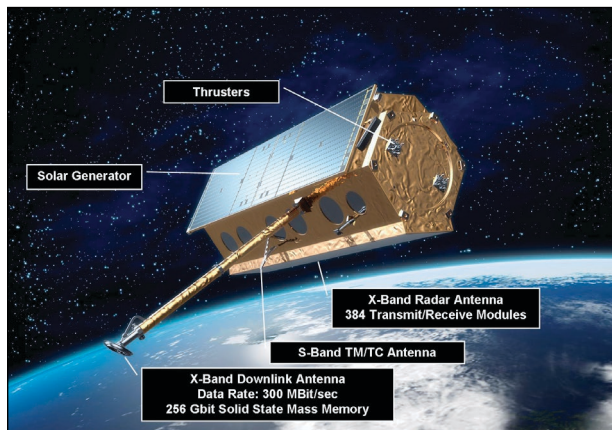


Figure 2. Artist view of the TerraSAR-X satellite. Note the solar generator (upper left), the boom with the X-Band downlink antenna (lower left) and the X-band radar antenna (lower right).

The commercial Geoscan RM15 instrument in a so called dual-pole configuration was used to collect electrical resistivity data. In this configuration, the two current probes are positioned in “infinity” (i.e. in a distance of around 50 m away from the measurement grid). The survey was conducted with two potential electrodes mounted at a frame in a fixed distance of 50 cm.

The data processing was done with Geoscan Geoplot and Golden Software Surfer again. To eliminate the natural variations of soil moisture and to enhance the visible archaeological remains, a high-pass filter was applied to the data.

4.3 Satellite radar

While the spatial resolution of the ground-based methods is tremendously high, the resolution of satellite sensors was enhanced in the last few years. Therefore, the new satellites like WorldView-2 offer a point spacing of 0.6 m in optical images. The improvement is even more dramatic in images created through Synthetic Aperture Radar. Before the launch of the German radar satellite TerraSAR-X in 2007 only a resolution of 5 – 25 m could be achieved. Now a resolution of SAR images of 1 – 2 m is available.

Synthetic Aperture Radar (SAR) provides a powerful tool for archaeological prospection from space. This method is based on a satellite sensor in the microwave frequency range, which is illuminating

the Earth’s surface with short electromagnetic impulses. Therefore, SAR is an active survey method and measurements are possible independently of daylight and weather conditions (Lee and Pottier 2009). Because of the specific reflection conditions in the microwave spectrum, the SAR image can show even structures which are smaller than the actual resolution of the sensor (Albertz 2009). This is a very important fact for the satellite-based prospection of archaeological sites like Palmyra that mainly consist of faint archaeological remains.

To get the highest possible resolution from space, a technical expedient, the so-called aperture synthesis, has to be applied. All targets are illuminated several times in one measurement cycle and the returned signals are correlated by their amplitude and phase. Afterwards, the data points are treated as if they were gathered by one long antenna (Albertz 2009; Bamler 1999; Lee and Pottier 2009). This is called the aperture synthesis and the method is named Synthetic Aperture Radar. SAR is the only possibility to get high-resolution radar data from space. Because of the huge distance between sensor and targets, a 15 km length physical antenna would be needed for a resolution of 1 m; by SAR this length is reduced to 5 m.

The first high-resolution German SAR-mission started in 2007 by the launch of the radar satellite TerraSAR-X. The project is a Public Private Partnership between the “Bundesministerium für Bildung und Forschung”(BMBF), the DLR and the Astrium GmbH and will last approximately until 2018. TerraSAR-X is a very compact satellite with a length of 5 m and a diameter of 2.4 m (Fig. 2). Nevertheless, it carries 384 transmitter/receiver antennae with an X-band radar frequency of 9.65 GHz. For further details on the mission, the interested reader is referred to e.g. Krieger et al. (2010) and Werninghaus and Buckreuss (2010).

TerraSAR-X data can be ordered directly at the DLR by a scientific proposal. As all of the standard processing steps applied to SAR data (especially the speckle reduction by a multi-look approach) lower the resolution, we used the original data of the satellite.

The advantage of using SAR instead of optical satellite images as a main space-borne method

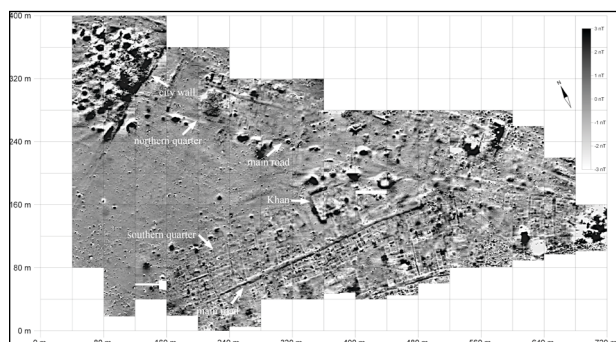


Figure 3. Magnetogram of the Hellenistic town of Palmyra. Overlay with the high-pass filter to visualize the stone walls in more detail. Caesium magnetometer Scintrex Smartmag SM4G-Special, Duo-Sensor-configuration, Dynamics: ± 3 nT in 256 greyscales, Sensitivity: ± 10 pT, Point density: 50×25 cm, interpolated to 25×25 cm, 40-m-grids (Becker and Fassbinder 1999).

is that by radar it is possible to detect buried archaeology as the active signal can penetrate the soil. Furthermore the method is independent on the daylight and weather conditions.

5. Results

5.1 Ground-based prospection

The magnetometry and resistivity prospection was carried out in March 1997 and 1998. Whereas the magnetometer prospecting covered ca. 20 ha in the area of the supposed Hellenistic town (Fig. 3 and 5 rectangle), the resistivity prospecting concentrated on two grids (60×40 m and 160×120 m) (Fig. 4 showing a high density of stone constructions). The results prove that the Hellenistic Palmyra was subdivided by three main streets oriented to the east and meeting in a V-shaped conjunction (Fig. 3). This conjunction astonishingly appears nearly empty and is only flanked by some kilns and grave monuments (Becker and Fassbinder 1999; Fassbinder and Linck 2012; Linck, Fassbinder and Buckreuss 2012). The northern one was underlain by a water pipeline, which can be identified by a higher magnetisation in the magnetogram and which has been proved by subsequent excavations (Plattner 2012).

The “Northern Quarter” was located north of this road (Fig. 3). It was characterised by a loose arrangement of large palaces with inner courtyards. One of the most striking buildings, the so-called

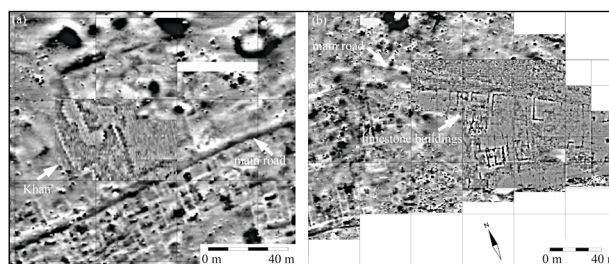


Figure 4. High-pass filter of the resistogram of (a) one of the palaces of the Palmyrene elite, (b) an area with dense irregular houses in the east of the town. Plotted over the corresponding part of the magnetogram. Geoscan RM15, Dualpol-configuration, Dynamics: $\pm 10 \Delta$ Ohm m, Point density: 50×50 cm, interpolated to 25×25 cm, 20-m-grids (resistogram), 40-m-grids (magnetogram) (Becker and Fassbinder 1999).

“Khan”, has been subsequently surveyed by resistivity prospection (Fig. 4a) and archaeological excavations. In the geophysical results it displays a high electric resistivity. Therefore, it can be inferred that it was constructed of limestone. The Khan consisted of several distinct rooms and apparently was erected in a building pit filled with burnt debris showing up as a positive magnetic anomaly (Schmidt-Colinet and al-As’ad 2000). Near the wadi, the magnetogram shows comparatively obscured, but nevertheless monumental floor plans. This could probably be explained by an extensive destruction of the buildings through periodic flooding and sedimentation by the wadi. This might explain why the Hellenistic town has been abandoned in Roman times and a new one has been constructed north of Wadi el Kubur (Fassbinder and Linck 2012; Linck, Fassbinder and Buckreuss 2012).

The “Southern Quarter”, on the contrary, was built with densely arranged small-scale houses (Fig. 3 and 4b). They were not limited to the main roads and extended to the minor roads. Therefore, this quarter had a nearly radial structure (Becker and Fassbinder 1999; Fassbinder and Linck 2012; Linck, Fassbinder and Buckreuss 2012). Small-scale excavations in selected parts of the magnetogram confirmed this interpretation and showed that the majority of the houses was constructed of weak magnetised limestone. On the contrary, some of the foundations show up as positive anomalies, which might signify that they were built with burnt mud bricks that have a higher magnetisation than



Figure 5. Optical image of the U.S. remote sensing satellite WorldView-2 in the area of ancient Palmyra. Clearly visible are the upstanding remains, but because of small sand accumulations at shallow buried walls even subsurface structures can be identified. Data take: 11. April 2011, Resolution: 0.6 m. The rectangle indicates the location of the magnetometry grid.

the surrounding soil. Unfortunately, geophysical surveys could not be undertaken in the southern limit of the quarter because of a nearby highly frequented modern road.

West of the Khan, a nearly empty area is visible in the magnetogram (Fig. 3). Schmidt-Colinet and al-As'ad (2000) supposed that this place could have been used as temporary storage yard for camel caravans or a place for nomad tents that did not leave many traces in the soil. This assumption cannot be verified by presented geophysical data, but it is obvious if one compares the results with those intensively used parts in the rest of the magnetogram.

In the westernmost part of the survey area, a city wall can be identified in the elongation of a hill ridge that served as a natural barrier and limited the town to the west. Outside of the wall a dense layout of extensively burnt structures can be seen that reach until the wall and are evidence of an extreme fire. Archaeological structures cannot be distinguished in this area.



Figure 6. Radargram of TerraSAR-X in the area of the ancient Palmyra. Especially upstanding structures can be distinguished very well, but even parts of the buried archaeology are detectable. Data take: 28. February 2011, Horizontal polarisation, Spatially enhanced mode, Resolution: 1 – 2 m.

5.2 Space-borne prospection

Whereas the ground-based surveys concentrated on the Hellenistic part of Palmyra, the space-borne images covered the whole archaeological site, including the Roman part and the surrounding graveyards.

For the analysis of optical satellite data, a WorldView-2 image recorded on April 11th 2011 is used. It has a resolution of 0.6 m and therefore even faint and small-scale anomalies at the surface can be identified.

The area of the ancient city is disturbed by several modern tracks and a row of regularly arranged holes of a quanat. Nevertheless, a perfect view on the upstanding ancient Palmyra can be achieved (Fig. 5). Several monuments are well preserved, especially in the Roman town. First of all, the Diocletian city wall surrounding the settlement can be clearly identified and several watchtowers and bastions are visible. In the interior part of the city, the good state of preservation of the official buildings is remarkable. In the eastern corner, the huge Bel-sanctuary can be seen. Even today, the 200 x 200m court with the surrounding wall and the temple are impressive buildings. Further to the west

the Nabu-sanctuary, the agora and the theatre are flanking the famous Great Column Road that runs through Palmyra from southeast to northwest. The westernmost part of the city is occupied by the late Roman military camp, whose layout is still visible today. In the living quarters, some of the roads and the adjacent buildings appear because of small sand accumulations at these shallow buried structures. It is remarkable that only the southwest to northeast running roads can be detected. The sand accumulation by the wind operates in this direction, and therefore the orthogonal linking roads remain unseen by optical images in the subsurface (Linck, Fassbinder and Buckreuss 2012). The same effect is reported by GORS (2002) in the analysis of IKONOS images. South of the wadi, the earlier Hellenistic town detected by magnetometry is visible. Only the Khan, excavated by a German-Austrian-Syrian mission, is visible at first glance. Nevertheless, a detailed analysis of this area offers several other buried structures. Some of the palaces in the “North Quarter” and the main roads, detected by magnetic prospecting, appear as slight sand accumulations in the satellite image (Linck, Fassbinder and Buckreuss 2012). Some of these walls were already reported as soil marks in aerial photos of the 1930s (Dentzer and Saupin 1996). In the west, the Hellenistic Palmyra is limited by a city wall already identified in the magnetogram, an elongation of the natural boundary of a nearby hill. The whole ancient settlement of Palmyra is surrounded by numerous burials. Remains of the graves that were sometimes constructed as tower tombs are aligned along the roads towards the city.

Even with a resolution of 0.6 m only structures preserved on surface can be identified. Buried structures can only be visualised by satellite radar. Therefore a radargram of the German satellite TerraSAR-X from February 28th 2011 was used (Fig. 6). The resolution of 1–2m ensures that at least the larger archaeological structures can be detected.

The rectangular corners of the upstanding ancient remains provide good reflectors for the radar waves: these structures are highly visible: the important monuments, known also from the optical images, like the Diocletian city wall, the Bel-sanctuary, the Column Road, the agora and the theatre, all appear very clearly (Linck and Fassbinder 2011; 2012; Linck, Fassbinder and Buckreuss 2012;

Linck, Fassbinder and Papathanassiou 2011) (Fig. 6). The city wall with its bastions and watchtowers depicts a very strong reflector, as it is 2.8 m thick (Wiegand 1932). The Nabu-sanctuary west of the huge Bel-sanctuary appears more detailed in the radar image than in the optical one because the preserved columns depict good corner reflectors for radar waves. Therefore, also the Column Road with its partitioning gates is visible very clearly. The Bel-sanctuary itself acts as one of the strongest reflectors, as it is one of the best preserved monuments. The buried archaeological structures appear mainly on the sub-pixel level and a time-consuming, detailed analysis was necessary to be able to map them. In the Roman town the layout of the entire rectangular grid of the roads can be drawn (Linck and Fassbinder 2011; 2012; Linck, Fassbinder and Buckreuss 2012; Linck, Fassbinder and Papathanassiou 2011) (Fig. 6). Because of the special reflection characteristics of radar waves, even some of the buried ancient buildings are detectable. Among these archaeological features, there is a considerable amount of so far unknown structures that are not mapped in the most recent map of the site by Schnädelbach (2010). The results hence prove that it is possible to map buried archaeological remains by satellite radar and it can be added to the promising and successful prospection methods.

The most striking object in the Hellenistic part is the excavated Khan (Fig. 6). Here the radargram shows several structures already known from the magnetic survey, e.g. the main roads that are very clearly visible because of their size, some minor roads, the city wall in the west and some walls of buildings. However, it is not possible to get all buildings in detail like in the magnetogram, since the resolution is limited to 1 m. Again, like in the Roman part, several so far unknown archaeological objects become visible, especially in parts that were not covered by the magnetometer prospection.

6. Conclusions

The geophysical prospection of intensively used ancient archaeological sites like Palmyra is very promising. This is proved by a huge amount of successful measurements (Benech 2007; Erkul, Stümpel and Wunderlich 2011; Fassbinder 2011). While the majority of such sites show magnetic anomalies of more than ± 30 nT, in Palmyra

comparatively weak anomalies of ± 3 nT occur. The relative weak magnetic anomalies in huge parts of the measured area do not prove the hypothesis that the Hellenistic part was abandoned after extensive destruction by fire. In fact, it is much more probable that the city was moved to the north of the wadi after several catastrophic flooding. The results enable furthermore the location of the Hellenistic part and make it possible to draw a detailed map of its radial layout.

The remote sensing approach by optical satellite images and Synthetic Aperture Radar provides the verification of already known parts of the city map of Palmyra. However, several new features can also be identified too. As TerraSAR-X can detect both upstanding monuments as well as buried archaeological features, it is evident that the X-band radar waves can penetrate into the ground. This fact has rarely been observed before and offers a totally new horizon for the use of high-resolution satellite radar in the archaeological prospection. Although remote sensing cannot substitute ground-based geophysical measurements, it can provide a good overview of the expected features. This helps to select suitable areas for more time consuming geophysical surveys, which can now be then undertaken only in pre-selected areas. The use of space-borne techniques is especially of high interest in the case of quite large archaeological sites that cannot be totally surveyed by excavations and ground-based methods. Moreover, it often provides the sole possibility of archaeological prospection in regions with a difficult political situation like Syria at the moment.

The opportunity to obtain SAR data with an outstanding resolution of 25 cm from TerraSAR-X through a proposed scientific project in autumn 2013 will enormously widen the usability of this method. This project will make available high-resolution data with only a slight difference in resolution between SAR and ground-based methods, making the comparison of the two data sets more effective.

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